

# ATOMMS: Active Temperature, Ozone, Moisture Microwave Spectrometer A LEO-LEO Occultation Observing System

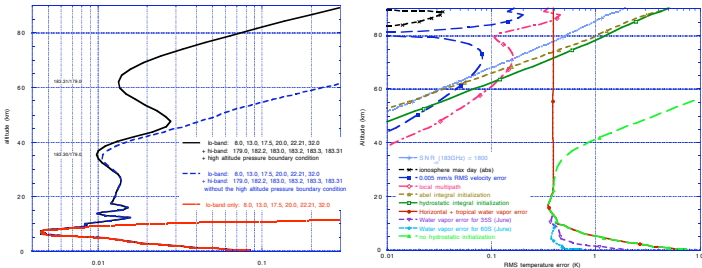
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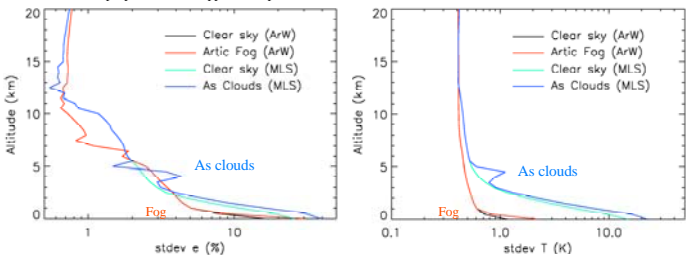
## Abstract

Understanding our evolving climate and reducing uncertainties about its future state depend critically on our knowledge of the 3D distributions of atmospheric water, and temperature and their variations and trends, trends to determine how climate is actually changing and variations to constrain the processes that must be accurately represented in predictive models. ATOMMS is a new radio occultation (RO) observing system that essentially combines GPSRO and the Microwave Limb Sounder (MLS) by actively measuring absorption as well as bending. The ATOMMS occultation system will transmit a set of tones at selected frequencies near the 22 and 183 GHz water absorption lines from one LEO satellite to another across the limb of the atmosphere. 195 GHz will be used to profile ozone. Water isotopes can be determined with additional frequencies. Profiles of delay and attenuation accumulated during signal passage through the atmosphere are inverted to recover profiles of atmospheric moisture, temperature and the geopotential height of pressure surfaces from the near-surface through the mesosphere. ATOMMS retains the strengths of GPSRO such as ~200m or better vertical resolution, high precision, and accuracy via self-calibration in both clear and cloudy air while overcoming key limitations by providing self-sufficient information to (1) resolve the wet-dry ambiguity and (2) initialize the hydrostatic integral and using much higher frequencies that (3) eliminate ionospheric sensitivity, avoiding subtle residual solar or diurnal cycle signatures that likely exist in the GPSRO results. ATOMMS is entirely self-contained with no reliance on external model, analysis or other remote sensing information and should be limited ultimately by our spectroscopic knowledge. The power of ATOMMS for climate monitoring, process studies and weather prediction have been discussed in Kursinski et al. (2005) and Anderson et al. (2007). Following years of development, NSF has recently funded us to build a prototype cm and mm wavelength ATOMMS radio occultation instrument and demonstrate its anticipated atmospheric profiling capabilities via a series of high altitude WB-57F aircraft to aircraft occultations. Initial demonstrations will occur in 2009.

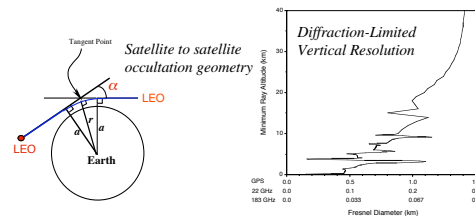
## Estimated Accuracy



Standard deviation of water vapor and temperature profiles (250 m vert. resolution) 0 to 20 km altitude for 4 sets of conditions:  
a. water vapor errors for tropical clear sky conditions,  
b. temperature errors for several different conditions. Note that by probing the width of the 118 GHz O<sub>2</sub> lines to directly determines temperature in the upper mesosphere accurate temperatures are achieved without any external information used to initiate the hydrostatic integral, creating very accurate, independent temperature profiles from the lowermost troposphere thru the upper mesosphere



Errors in individual water vapor and temperature profiles (250 m vert. resolution) 0 to 20 km altitude for 4 sets of conditions:  
(1) Arctic Winter (ArW) clear conditions (2) ArW with a 1 km thick, supercooled fog layer with LWC = 0.15 g/m<sup>3</sup>  
(3) Mid-latitude Summer (MLS) clear conditions  
(4) MLS with a broken deck of altocumulus (As) clouds between 4.5 and 5.5 km altitude with LWC = 0.3 g/m<sup>3</sup>.  
Errors include estimated effects of turbulence.  
Larger near-surface errors for warmer conditions are due to reduced orthogonality between refractivity and extinction coefficient under very wet conditions (Kursinski et al. 2002)  
Accuracy improves with averaging, limited ultimately by spectroscopy



## Summary: Combined Occultation Bending Angle and Absorption Retrieval

### The measurements

- Each transmitter transmits multiple signals across the Earth's limb to a receiver that downconverts, filters, digitizes and records the complex signal spectrum.
- The time varying amplitude and frequency of each occulted tone are extracted in subsequent processing.

### Profiling Index of Refraction, $n$ :

- The occultation geometry is precisely reconstructed using GPS
- Measured signal frequencies + geometry => Atmospheric Doppler profiles => bending angle profiles => refractivity profiles via an Abel integral transform (e.g., Kursinski et al., 1997)

### Profiling Extinction Coefficient, $k(f)$ , at several frequencies:

- Amplitude measurements => integrated absorption profiles => profiles of extinction coefficient via an Abel transform or equivalent (e.g., Kursinski et al., 2002)

### Determining water vapor, temperature...

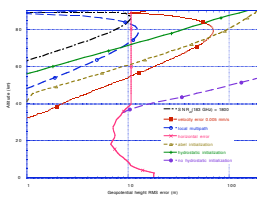
- $n$  and  $k(f)$  are combined with spectroscopy and hydrostatic equilibrium to directly and uniquely determine atmospheric density, temperature, pressure, water vapor and ozone vs. height.

### Bending Angle Forward and Inverse Abel Integral Transform Pair

$$\alpha(a) = 2a \int_{\eta}^{\infty} \frac{1}{\sqrt{r^2 n^2 - a^2}} \frac{d \ln(n)}{dr} dr \Leftrightarrow n(r) = \exp \left[ \frac{1}{\pi} \int_{a_1}^{\infty} \frac{\alpha}{\sqrt{a^2 - a_1^2}} da \right]$$

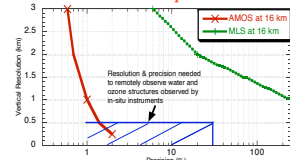
### Opacity and Absorption Coefficient Abel Integral Transform Pair

$$\tau_m = \int_0^{\infty} k dl = 2 \int_0^{\infty} k \frac{n dr}{(n^2 r^2 - n_0^2 r_0^2)^{1/2}} \Leftrightarrow k = - \frac{1}{2\pi} \frac{d\tau}{dr} \bigg|_{a=a_0} \frac{d\tau}{da} \frac{da}{(a^2 - a_0^2)^{1/2}}$$



Standard deviation of ATOMMS geopotential height error vs. height

## Importance of combined vertical resolution and precision:



Comparison of vertical resolution vs. precision of individual MLS and ATOMMS (AMOS) water vapor profiles near the tropical cold-point tropopause. ATOMMS provides the combined vertical resolution and precision needed to determine variability to constrain processes and reveal behavior invisible to passive sensors such as ubiquitous fine scale layering observed by in-situ observations (e.g. Newell et al., 1999). With ATOMMS we will be able to globally determine how stability is evolving throughout the free troposphere as our climate changes.

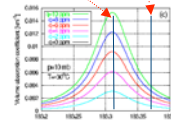
## Calibration

### Self-calibration

- Occultations are inherently self calibrating because the signal amplitude and frequency are measured immediately before or after each occultation
- Each profile of optical depth,  $\tau$ , is determined as the logarithm of the signal amplitude measured above the atmosphere divided by the amplitudes measured during the occultation
- Renormalizing every occultation **eliminates long term drift**

### Reduction of unwanted amplitude variations during each occultation

- At least 2 occultation tones are used to probe each absorption line
- One tone frequency is on the absorption line and the other is farther off the line
- The differences in the optical depths & extinction coefficients measured at the two frequencies are used in integral transforms
- This approach minimizes unwanted amplitude variations such as gain variations due to antenna pointing, scattering due to ice clouds and scintillations due to turbulence.



## Aircraft-Aircraft Occultation Demonstration

Our MRI proposal has recently been funded by NSF to

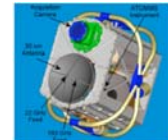
- build a prototype ATOMMS instrument (one for each aircraft)
- perform a set of occultation demonstrations between two high altitude aircraft.

### The ATOMMS instrument prototype

- will measure atmospheric Doppler shift to derive refractivity
- will probe the 22 and 183 GHz water lines
- will probe the 195 GHz ozone line
- may probe the 203 GHz H<sub>2</sub><sup>18</sup>O line to demonstrate the isotope capability.

### Aircraft occultations:

- Two NASA WB-57F aircraft will each carry an ATOMMS instrument mounted on its optical bench in its nose (developed to precisely image the shuttle during launch)
- The aircraft fly towards one another from initial positions over the horizon at high altitude (~20 km) creating a rising occultation.
- The transmitter portions of the ATOMMS instruments send signals across to one another through the atmosphere.
- ATOMMS receivers downconvert, digitize & record the occulted signal complex spectrum.
- We subsequently analyze the spectra according to the procedures summarized to the left to profile temperature, water vapor, ozone and pressure at altitudes below the aircraft altitudes
- The aircraft occultation demonstrations will occur in 2009 and 2010.



## Summary of ATOMMS Features

ATOMMS will determine the 4D thermodynamic state and constituents of the atmosphere well beyond present capabilities.

- Wide dynamic range yields temperature, moisture and pressure profiles from near surface to ~mesopause
- Self calibrating, relative measurements normalized to signal properties measured above the atmosphere immediately before or after each occultation eliminate long term drift
- Use of cal tones dramatically reduces unwanted amplitude variations during each occultation
- Stand-alone retrievals (no a priori estimate required to produce a unique profile solution)
- Provides  $\leq 200$  m vertical resolution, well beyond that of passive sensors
- Limb viewing horizontal averaging yields more representative profiles than point measurements
- Provides very high precision of individual profiles to capture variability
- Provides still better absolute accuracy with averaging limited ultimately by spectroscopy
- Similar performance in clear and cloudy air
- Additional frequencies will determine additional constituents including water isotopes
- High frequencies are 4 orders of magnitude less sensitive to ionosphere than GPSRO eliminating subtle solar and diurnal cycle leakage into GPSRO refractivity profiles and extending middle atmosphere RO profiling to ~mesopause
- Particularly well suited to difficult and important upper trop/lower stratosphere regime
- Can accurately profile middle atmosphere winds above 30 km as well

## References

- Anderson J., et al., 2007, The climate benchmark constellation: A critical category of small satellite observations, [http://map.nasa.gov/clarreo\\_materials.html](http://map.nasa.gov/clarreo_materials.html).  
Kursinski, E. R., et al., 1997, *J. Geophys. Res.*, **102**, 23429-23465.  
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Newell, R. E., et al., , Ubiquity of quasi-horizontal layers in the troposphere, *Nature*, **398**, 316-319, 1999.